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(72) Inventors: WILLIAM DAVID GREGORY
LARRY HOWARD CAPOTS
JAMES PAUL GEORGE
RICHARD JANIK

(54) SYSTEM AND METHOD FOR IDENTIFYING SAMPLES HAVING CONDUCTIVE PROPERTIES

(71) We, GEORGETOWN UNIVERSITY, a non-profit Organisation organised according to the laws of the District of Columbia, United States of America, of 37 & 0 St., N.W. Washington D.C. 20057, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

Metal detection systems have been used for more than thirty years, and have been capable of determining the presence or absence of a metallic object. Such systems have found many applications in various fields, and more recently, such systems have been finding widespread use as weapons detector devices. However, these systems when used for weapons detection have not been able to readily distinguish between various types of metallic objects.

These systems use an induction coil to which an oscillating signal is applied. Detection readings heretofore have been limited to a general determination as to the presence of a metal object with no precision in the identification process.

It has now been discovered that information can be developed which will permit this type of detection system to make specific identification of objects having conductive properties, and to give repeatable data for a specific object.

Previous systems have limited application because of their inability to distinguish between different types of objects, and in the use of these systems for detection at airports, there has been a persistant false alarm problem.

With the development of the system of this invention, it is now possible to accurately obtain information with respect to the type of conductive object disposed in the coil field, including information as to the various metallic components that are contained in it if there is more than one metal. This makes it possible to readily screen for different types of metallic objects of interest to preclude false alarms.

In addition, the system of this invention represents a break-through in that accurate repetitive readings can be obtained which make it possible to apply such systems to other areas, such as metal classification and where the material to be tested is in the form of a conductive solution.

This invention relates to metal detection systems for objects having conductive properties, and particularly to a more advanced and sophisticated type of detection sytem than previously possible.

This system makes it possible to accurately check for a specific object and can be used as a means of sorting different kinds of metal, even making it possible to distinguish between different types of hand guns.

Essentially, this new detection system is based upon the discovery that in a previously balanced coil system, after introduction of a conductive or of a metal sample, the true resistive component of the impedance occurring in the coil system changes due to eddy current loss. When the true resistive component is divided by frequency applied

$$\frac{(\Delta R)}{f},$$

it gives a value which varies with frequency and peaks at a single peak frequency. This peak frequency value is proportional to the cross-sectional area of the object in a plane

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transverse to the coil. In addition, the peak frequency, or that occurring at a maximum

$$\frac{\Delta R}{f}$$

value, has been found to be proportional to the resistivity of the sample divided by its cross-sectional area.

However, these results will not occur unless very accurate measurements are made and all extraneous effects caused by the various system components, such as the frequency generator, coil and detection circuits, are taken into consideration. That is, in order to obtain a true picture of the effect of the sample, it is necessary to look only at the true resistive component change in the coil system.

The true resistive component change can only be obtained if the output signal is referenced to within one degree of the phase of the signal applied to the input coil. Unless this phase relationship, which is hereafter referred to as zero degree phase shift, is kept, the results obtained will not provide the accuracy required for most contemplated uses of the system.

According to the invention there is provided a system for identifying samples having conductive properties, comprising frequency generating means operable to provide output signals at a plurality of selected periodic driving frequencies; coil means connected to said frequency generating means and responsive to output signal having a selected periodic driving frequency for providing a magnetic field which varies in accordance with said selected periodic driving frequency, said coil means producing an output signal having a phase and said coil means being responsive to placement of a conductive sample in said magnetic field to undergo an impedance change having a true resistive component; and means for obtaining the true resistive component of the impedance change at said selected periodic driving frequency by referencing the phase of the output signal of said coil means to within 1° of the phase of the output signal of said frequency generating means for said selected periodic driving frequency, whereby to develop signature data to identify said sample.

In a particular embodiment said frequency generating means includes output leads, said coil means including an input coil comprising a hollow coil connected across said output leads of said frequency generating means, said coil means further including a secondary coil arrangement including two matched hollow coils connected in bucking relationship and axially arranged, one with respect to the other, and adjacent to said input coil, a balancing variable resistor is connected to said secondary coil arrangement, and a phase sensitive detector is connected to a junction connecting said two matched hollow coils of said secondary coil arrangement for measuring said true resistive component.

A further aspect of the invention provides a method of identifying samples having conductive properties, comprising the steps of providing a coil system having an input coil; generating in turn a plurality of signal frequencies; applying at least one said signal frequency to said input coil of said coil system to produce a magnetic field; introducing a sample into said magnetic field of said coil system so as to cause an eddy current loss; obtaining, for said at least one signal frequency applied to said input coil and by referencing the phase of the output signal of the coil system to within 1° of the phase of the output signal of the frequency generating means, a true resistive component of said eddy current loss so as to develop at least one true resistive component value; dividing said at least one true resistive component value by said at least one signal frequency applied to said input coil to develop at least one quotient value; and using said at least one quotient value as a function of signal frequency applied to said input coil to obtain signature data for identifying said sample.

A further method aspect of the invention for determining response characteristics for sameples having conductive properties comprises the steps of: providing a coil assembly; applying a plurality of periodic signal frequencies in turn to said coil assembly so as to provide a magnetic field for each signal frequency; introducing a plurality of the same kind of metal samples of different cross-sectional areas to said magnetic field of said coil assembly; measuring, for at least one periodic signal frequency applied to said coil assembly, the true resistive component of voltage unbalance in an output signal from the coil assembly caused by introduction of each of the metal samples; and compensating for phase-shift in the coil assembly with respect to the phase of said at least one periodic signal frequency applied to said coil assembly, whereby said true resistive component value is obtained at zero degree phase-shift, the phase of the output signal of said coil assembly being referenced to within 1° of the phase of the applied periodic signal frequency.

The invention will be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a mutual inductance detector circuit.

Figure 2 is a graph of the secondary coil signal illustrating the phase shift caused when a metal object is placed between the coils of Figure 1.

Figure 3 is a vector diagram of the voltage amplitude vector which shows the resistive component.

Figure 4 is a graph of resistive component divided by frequency versus frequency for a metal object.

Figure 5 is a plot of resistive component peak values divided by peak frequency versus the reciprocal of the peak frequency, showing the linear relationship in peak values when cross-section area and cross-section geometry of a metal object vary.

Figure 6 is a plot similar to Figure 5 showing linear relationships for various types of metal objects.

Figure 7 is a plot similar to Figure 4, showing peak curve signal where plural pieces are disposed between the coils of Figure 1.

Figure 8 shows a second type of detector circuit using a balanced bridge arrangement.

Figure 9 shows another type of detector circuit which uses a split coil balanced secondary.

Figure 10 is a plot of resistive component divided by frequency versus frequency which gives the signature for a Smith and Wesson stainless steel revolver.

Figure 11 is a plot of resistive component divided by frequency versus frequency showing the signature for a Titan .25 revolver.

Figure 12 is a block diagram of the detector system where a minicomputer is used for comparison of received signature with those of known objects.

Figure 13 is a block diagram of the software elements of the detector system of Figure 12, and

Figure 14 is a block diagram of a detector system showing phase sensitive detection where analog switch circuits and digital logic integrated circuits are used.

Referring particularly to Figure 1, a detector system 10 is shown in which the alternating current signal source 12 supplies a signal to the input or primary coil 14. The secondary coil 16 is connected to a phase sensitive detector 18, which will pick up variations in the secondary coil signal when a metal object 20 is disposed within the field, schematically shown between the input or primary coil 14 and the secondary coil 16. Coil diameter can be any size from a small sample coil of 12″ to a 6′ walk-in coil. The object can be placed either within the coil for maximum response or outside but close to the coil as long as it is within the generated magnetic field.

It has been found that tests involving metals can be made at frequency ranges from 100 to 10,000 hertz. However, if the frequency is increased to the 1-10 megahertz range, test results can be obtained giving particular resonse characteristics for samples having conductive properties. Such samples may be, for instance, metal powder-type explosives, conductive animal tissue and aqueous and ionic solutions and suspensions.

The vector diagram in Figure 3 shows the situation when a metal object such as 20 is introduced to the field between the input or primary coil 14 and the secondary coil 16. The vector A is shown at 32. This vector makes an angle 34 with the zero degree phase line and represents the amount of displacement shown in Figure 2 on the lower graph at 30. A reading of interest for purposes of this invention is the resistive component Δ R shown at 36 which runs along the zero degree phase line. This value is the reading that is picked up by the phase sensitive detector 18. It is one of the essential values used in connection with the principles of this invention. It makes it possible to find peak eddy current loss by plotting the resistive component divided by corresponding frequency against that frequency. This is shown in Figure 4 for a metal sample of three different cross-sectional areas. The larger sample A is represented by the curve 38 which has a peak as shown at 40. This plot will give what is termed the peak frequency, as shown by the dashed line 42. From this plot the value of peak frequency and matching resistive component divided by frequency is found.

The sample B, which is of smaller cross section than that of sample A, but of the same material, gives a peak curve 44 with a peak 46 which is less in amplitude than that of the larger sample A. The peak frequency line 48 shows that the peak frequency for the smaller sample is higher than that of the larger sample.

Similarly, sample C is made of the same metal as samples A and B and is of smaller cross-sectional area than sample B. The peak frequency curve 50 for sample C is somewhat flatter and has a peak value 52 of considerably smaller amplitude than either of the other samples. The peak frequency line 54 shows that it also has a considerably higher peak frequency value.

It will be noted that the peaks for all three samples shown in Figure 4 are in alignment, and a plot using the reciprocal of the frequency, as shown in Figure 5, based upon peak

frequency values for these three samples gives a straight line 58. The ordinate for amplitude in this graph is the resistive component divided by the peak frequency, while abscissa is the reciprocal of the peak frequency values.

A plot of peak frequency values for samples A, B and C is shown at 58, 60 and 62, respectively. The dashed line 64 represents a geometrical factor. It has been found that the slope of this line will vary slightly with changes in cross-sectional configuration. In this graph, line 56 shows readings taken with a test object of square cross section. The dashed line 64 indicates the change in slope that will be expected where there is a considerable change in geometry.

It should be noted that these peak frequency values will vary considerably depending upon the type of metal used, inasmuch as metal resistivity is a major factor. This can be clearly seen in a review of the graphs shown in Figure 6.

Figure 6 is a detailed graph of the same type as shown in Figure 5 and shows the response characteristics for different metal samples. It should be noted that in this graph, coil configuration is taken into consideration for the values given, in that the peak amplitude value includes the resistive component divided by the peak frequency, as well as the reciprocal of the number of turns in the input coil and the reciprocal of the magnetic induction expressed in Webers per square meter

$$\left(\frac{\Delta R}{f} \cdot \frac{1}{NB}\right).$$

The abscissa for this graph is the reciprocal of the peak frequency expressed in hundredths of a second.

The band shown on the graph for the different types of metal have a wide range of slope values. The primary factor in determining the slope of the bands is the resistivity of the metal involved. Band 66, which represents the linear range of peak values for stainless steel, has a very high resistivity, as compared to the more conductive metals, such as copper and aluminum. The band 68 shows the range of peak frequency values for steel. This band, as well as all of the other bands shown on the graph, fan out from the origin 70. The wide difference in slopes of each of the bands is attributable to the correspondingly wide range of resistivity values for the metals shown. The following table for metals and their corresponding resistivity illustrates this:

Metals	Resistivity (Micro-ohm - Centimeters)
Copper	1.7
Aluminum	4.0
Brass	7.0
Steel	10.0
Stainless Steel	72.0

The slightly diverging lines determining the width of each band, such as lines 72 and 74, reflect small changes in slope that are due to geometrical cross section variances of the sample. Peak frequency for brass, aluminum and copper are shown respectively by the bands 76, 78 and 80.

With respect to variation in cross-sectional geometry, the sample under test may be defined as having a geometric ratio, G, which is equal to the width squared divided by the heighth squared i.e., $G=a^2/b^2$. This factor is taken into consideration on plots for the bands shown for each metal, where the lower line represents a square block (G=1) test specimen, while the upper line represents a rectangular block with a width twice that of the height (G=4).

For example, referring to the aluminum band 78, of Figure 6, the lower line contains the point 82 at which a one inch square aluminum sample (G=1) could be found. The reciprocal peak frequency value is approximately .58 hundredths of a second, and the resistive component amplitude,

$$\frac{\Delta R}{f_p} \cdot \frac{1}{NB_o},$$

has a value of slightly less than 7.5.

Correspondingly, point 84 lies on the line defining the upper limit (G=4) for the

aluminum band 78. This would be the point giving a reading for an aluminum object of one square inch cross-sectional area which has a width twice its heighth. It will be noted that point 84 has a slightly higher amplitude value and a slightly lower time value for the reciprocal of the frequency. Experimental data for the same cross-sectional dimension blocks for the other metals gave values for all of these metals in which the amplitude for the one inch square test specimen is about the same as those of points 82 and 84 - specifically, around a value of approximately 7.5. For example, a square copper test sample with an area of one square inch would have an amplitude of 7.5 and a reciprocal peak frequency value of 1.4 hundredths of a second.

Although, it is seen that variations in cross-sectional geometry have a slight effect on slope, changes in cross-sectional area will not affect the slope but will very greatly affect both amplitude and reciprocal frequency values. They will, however, be proportional and fall along the G=1 line for each band where the test specimen is square. For example, for a square test specimen of one-half inch square cross-sectional area, the peak frequency point will be midway between the origin 70 and point 82. For a square aluminum test object having a cross-sectional area of two square inches, the peak frequency values will lie along the G=1 line at a point which is twice the distance from the origin 72 as is the point 82.

To use the graph of Figure 6 to determine resistivity and cross-sectional area of an unknown object, values for amplitude and the peak frequency reciprocal are obtained from a graph line Figure 4. Where the reciprocal of a peak frequency has a value of .45 hundredths of a second, the vertical reference line 86 is established. Where the amplitude valuation

$$\left(\frac{\Delta R}{f_p} \cdot \frac{1}{NB_o}\right)$$

is 6.5×10^{-4}, the horizontal reference line 88 is established. The intersection of both of these lines at 90 indicates that the unknown object in the coil system is made of aluminum and has a cross-sectional area of slightly less than one square inch.

As can be seen from the manner in which the respective bands are separated from each other, it is possible to readily distinguish one type of metal from the other with the resistive component and peak frequency reciprocal values even if considerable difference in cross-sectional shape exists.

The preceding discussion has assumed a single metal object. In most detection situations, there are several different objects that have several different metallic components which it is desirable to detect. In these cases, each of the different metals will product its own peak signal. For example, in Figure 7, three pieces are sensed by the detector system. Piece 1 generates curve 92, piece 2 generates curve 94, and piece 3 generates curve 96. The resultant envelope includes a single trace with three humps representing the peak frequency and amplitude value for such piece or metal component. It is assumed that each of these pieces could be of a different metal and of a different cross section. The detection system using the change in resistive component is sufficiently sensitive to distinguish the peaks for each of the different metal pieces as the different frequency values are applied.

Figure 8 shows a balanced bridge detection system which can be used. This balanced bridge arrangement is preferred over the the detection system of Figure 1, in that it is more readily balanced and does not have serious perturbations on measurements. The signal frequency generator 98 is disposed across the bridge as shown at one end of the sensing coil 100, and at the corresponding end of matching coil 102. Both coils have similar values. Resistance 104 forms another arm of the bridge, and variable resistance 106 which generally matches the value of resistance 104 forms the last arm of the bridge. The phase sensitive detector 108 is connected between the common junctions of the coils 100 and 102 at one side and the common junction of resistors 104 and 106 on the other side. The reading of the phase sensitive detector will assist in adjustment of the variable resistor 106 to get a balanced condition across the bridge prior to introduction of the test object 110. When the test object 110 is introduced to the field surrounding coil 100, an eddy current loss will unbalance the bridge and the phase sensitive detector will read the resistive component value which must be referenced to the coil 100 signal.

Figure 9 shows another type of phase sensitive detection circuit arrangement which has proven to be very satisfactory. The signal frequency generator 112 is connected across the input coil 114. Secondary coils 116 and 118, which are of equal value, are connected at their lower ends. Fixed resistor 120 is connected to the upper end of coil 118 at one end and has its other end directly connected to a variable balancing resistor 122 which is connected to the upper end of coil 116. A phase sensitive detector 124 is connected across the common connections of coils 116 and 118 at one end and the common connection between resistors

120 and 122 at its other end. The metallic object 126 is disposed between the input coil 114 and the split secondary coil assembly made up of coils 116 and 118. This detector system provides maximum sensitivity and ease of balance with the variable resistance 122.

The actual signature trace that is developed by a complex object, such as a gun, is shown in Figures 10 and 11. Figure 10 shows the signature S for a Smith and Wesson .38 caliber stainless steel revolver. The ordinate is the resistive component divided by the frequency and the abscissa is the applied frequency values. The trace has a high peak at 128, which indicates the barrel of the revolver, and the low portion 130. In order to obtain such a signature, it is necessary to apply some thirty different frequencies over the 10,000 hertz range. For automatic analytical purposes, such as used with curve analysis, an average curve envelope is obtained as shown by the curve 132. This would then be analyzed and compared to a series of stored signatures in the device.

Figure 11 shows the signature S for a Titan .25 revolver. This signature has a high pronounced spike at 134, and peaks at 136 and 138. Both of these signatures are very dissimilar in appearance. They have peaks at different frequencies and the signatures are at different amplitude levels. Digital and other comparative techniques make it possible to readily distinguish between each of these two signatures. The signatures for other weapons and other types of objects are just as distinctive as these two examples.

In airport detection systems, where the individual passing through the coil area may carry numerous types of metal articles, it is also possible to readily pick out the existance of a gun signature. The various articles add to the overall signal envelope, but the gun signature is still readily distinguishable. In almost every instance, the signal produced by the gun will be the predominant signal.

Figure 12 gives a block diagram arrangement of the hardware components of the weapons detector system. The multiple frequency source 140, which is the equivalent of the frequency signal generators of Figures 1, 8, and 9, supplies a signal to the balanced circuit, indicated here at 142. It is also possible to use a balanced system including a bridge with a single coil. The arrangement is similar to that shown in Figure 8, except that a resistive element is used in place of coil 102 of Figure 8, and the variable resistance 106 of Figure 8 now contains a variable capacitor in parallel with it.

In Figure 12, the multiple frequency source also transmits a frequency to the multiple frequency timer and controller 144. The frequency range will be from 100 to 10,000 hertz and can be spanned with approximately thirty different frequencies within this range. This is the frequency range shown in Figure 11, and is more than adequate for all of the situations for which the system is designed.

The multiple phase sensitive detector section 146 will receive the signals from the bridge, as well as from the timer and controller circuit 144. The phase sensitive detector output, as well as the output from the multiple frequency timer and controller section 144, are supplied to the minicomputer 148. Typically, this is an 8K memory 16 Bit word minicomputer.

With respect to the computer, an analog to digital converter is used to interface the phase sensitive detector circuitry to the computer. The empty coil response of the induction coil electronics, and its response to a known resistance change are stored in the computer memory. With regard to Figure 13, blocks 152 and 154 are used to calibrate the coil electronics and produce true zero degree phase component data.

The computer will have comparison capability with stored data signature values to which the incoming digital signal input is compared. If there is a match for any of the stored signals representing a weapon or other item for which a check is to be made, the computer sends the signal to an alarm circuit 150.

Instead of using the analog phase sensitive detector techniques to separate the zero degree component at each frequency, it is possible to achieve the same results with the use of digital Fourier transform techniques. This would involve replacing the individual analog phase sensitive detector units for each frequency and using a good broad band amplifier at 146 instead of the phase sensitive detector units. This, together with an accurate time base generator for use as a clock, would make it possible to use the Fourier technique. The data would be studied at fixed time intervals and analyzed in the minicomputer by standard Fourier transform techniques.

Figure 13 gives the basic logic steps and functions of the system of Figure 12 using the phase detector. Initially, there is the bridge calibration routine illustrated in block 152, followed by the phase sorting routine indicated in block 154.

The zero degree phase values then are sorted as indicated in block 156, producing peak zero degree phase resistive component values for particular frequency values.

The threat data file 158 is fed into the search and compare block 160 for comparison with the input signals which will be supplied from the peak sorting block 156. A comparison is made in block 160 and if there is a match of threat and incoming active data a signal is sent

to the alarm block 162.

Figure 14 is a more detailed block diagram for a proposed detector system. A crystal oscillator 164 is used to generate a standard frequency which is supplied to a variable frequency divider network 166. The output is supplied to a frequency divider chain 168 which supplied three outputs. The first goes to the control divider chain block 170. The second output goes to the square wave adder section 172 and subsequently to the signal condition or block 174 and power driver 176. The output from the power driver is supplied to the sample coil bridge 178, and its output supplied to the phase sensitive detector section 180.

With respect to the phase sensitive detector circuitry, it is possible to use standard analog switch devices which can readily be used with the sample and hold circuitry necessary for computer interfacing.

The frequency dividers are J-K flip flops which provide zero degree phase and 90° reference square waves at eight octave frequencies simultaneously. Three starting frequencies provided consecutively by the variable divider, permit sampling a total of 24 frequencies between about 70 Hz and 12.5 Kilohertz.

The square waves drive the reference channels of the phase sensitive detectors directly, and the in-phase components are analog added to form a composite square wave containing eight frequencies. This wave form is integrated in a conditioner to form a composite triangle wave. The high frequencies are preamplified in the adder to make the triangle amplitude the same for all frequencies. Power operational amplifiers apply this signal to the bridge, and the off-balance signal is amplified and phase detected.

When a fixed number of cycles have occurred, the phase detector output is sampled and held until the computer has accepted it. The starting frequency is changed, and the process repeats. When all the frequencies have been sampled, the control divider stops the process.

Operation

As to operational aspects of the system, it has been found that the phase relationships are critical in measuring the true resistive component. Inasmuch as measurements of voltage unbalance are made in the 10 to 100 microvolt range and involves a factor of 1 in 10,000, all equipment must be very stable and accurate to preclude introduction of phase shifts which would make it impossible to maintain the zero degree phase relation required for measurement of true resistive component impedance change in the sensing coil.

The coil itself must be extremely stable, and it has been found that this stability must be held to at least one part in ten thousand, with a preferred stability of one part in one hundred thousand. Spacing between adjacent turns of the coil, temperature stability of the wire or shielded from temperature variation, and preclusion of displacement of the turns due to vibration are factors of importance. The turns in the coil are preferably spaced from one to two centimeters apart to reduce interturn capacitive effects. The coil should be as free as possible from all extraneous effects.

The oscillator circuit itself must be extremely stable to preclude phase wiggle or shift due to temperature, vibration, or instability of its elements. Signal output variation should be held to less than one tenth of a degree when using Fourier techniques and one-half degree when using phse sensitive detectors. Oscillator elements must have low thermal change characteristics, and be within about one tenth of one percent of their value while operating to preclude unacceptable variation jitter in output signal. Similar rigid requirements are necessary for the bridge and measuring elements.

The phase angle in the input coil is of importance, and all voltage data must be referenced to it. Corrections for phase shift of the various circuit elements must be made when measurements to determine charactérics, for example the voltage phase angle, of the voltage in the signal unit are made either upstream or downstream from the input coil.

The several system coils should be as identical as possible and they should be shielded from temperature variation. All of these restrictions are necessary to give consistent repetitive results where frequently the volume of the sample is of the order of a cubic centimeter while the coil volume is a cubic meter.

It has been found that this requirement can be met by previously determining what this angle is with respect to other equipment, such as the oscillator, and making a correction for it. The simplest manner of determining the phase angle in the input coil is to place a resistor in series with the input coil and measure the phase angle of the signal passing through it. This will allow determination of the resistive portion of the coil system output signal caused by the unbalance of a metal object only. Using the known resistance in series with the coil makes it possible to obtain corrective data. In this case, data is obtained on both the plain coil response and the coil and resistor response and is useful in a correction equation which takes into account both the real and imaginary values of the voltage. This information can readily be programmed into the computer and incoming data can normally be modified to

make the correction for zero degree phase shift.

Adjustments for zero degree phase can then be made either in the instrumentation, such as in the phase detector circuitry, or calibration data can be obtained and incoming data modified accordingly, such as with a computer system using a Fourier technique to obtain the true resistive component.

The above-described calibration technique which involves introduction of a known pure resistance in series with the sensing coil provides knowledge as to the portion of the sensing coil input signal unbalance caused by introduction of a metallic object.

The method used to determine what portion of the unbalanced output signal corresponds to this resistive change will, of course, depend upon the specific balancing circuitry employed.

In the case of the measurement circuit using a bridge arrangement, although it is more easily balanced, it has many extra circuit components between the sensing coil and the output signal. There must be compensation for the extra circuit elements to determine the phase shifts introduced by them, and they must be compensated for, either electrically, or by computation subsequent to measurement.

Once the various phase shifts in the system are known, it is a matter of applying the appropriate correction in phase shift so that the resistive component values obtained be referenced to zero degree phase existing in the input coil. As mentioned above, the correction should be made to bring the resistive component vector to within one degree of the resistive component of the coil system impedance.

The adjustments for zero degree phase can be made in the intrumentation, or calibration data applied to the measurement to make the necessary correction for zero degree phase shift.

It has been found that referencing to the oscillator output signal is a most convenient method of obtaining a good fixed phase base. Correction for shift between the oscillator and the sensing coil must be made to obtain the zero degree phase line, and once this is obtained, appropriate referencing can be made to the phase of the output signal obtained from the circuit and correction made so that they are within one degree of being completely in phase with each other. It should be kept in mind that the correction equations taken into account both the real and imaginary values of the voltage. This information can readily be programmed into a computer and the incoming data can normally be modified to make the correction for zero degree phase shift.

It has been found that the value obtained when there is zero phase shift will be within plus or minus five percent. Any greater displacement than the plus or minus one degree tolerance will result in a substantial loss of accuracy such that the data will not be repetitive for similar samples. The straightline relationships as shown in Figure 6, for example, will not be usable.

In a complex object it is unnecessary to use specific peak frequency values, since many peaks, one for each of the various metal components of the object to be checked, will appear. The selection of thirty frequencies in the range of from 100 to 10,000 hertz will give a typical range and will produce the results shown for the signatures of interest for guns and also permit easy identification of other types of objects. To develop the signatures as shown in Figures 10 and 11, frequency values are chosen for relevancy to both the resistivity of the metal being sought, as well as the estimated cross-sectional area.

With reference to the two Figures 10 and 11 showing the signature traces, there will be a very great correlation between the test sample and the actual sample encountered. As to different types of objects with slight variances in design and makeup, as in different types of guns, the signatures will vary significantly because of the differences in cross-sectional area and resistivity of the various components of which the article is made.

For identification, the computer can store the various signatures for the known objects to be checked for by the detection system, correct the incoming signal for zero degree phase correlation with the input coil system signal, and then compare the incoming signal data from the unknown object disposed in the sending coil with the stored signatures to determine whether there is a match.

The object is physically placed within the sensing coil itself. Frequency reciprocal values change greatly with changes in cross-sectional area. This should not be confused with the changes in cross-sectional geometry which have some effect, but not the appreciable effect which results from resistivity and cross-sectional area changes in the sample, i.e.

$$f_p = \frac{K\rho}{A}.$$

To develop the signatures as shown in Figures 10 and 11, frequency values are chosen for

relevancy to both the resistivity of the metal being sought, as well as the estimated cross-sectional area.

Coil configuration and geometry are important to note since the signature traces will be affected by them. In this respect, the terms N and B_o will be noted in Figure 6. This gives some guidance with respect to coil design which is a factor in response characteristics of the system.

The expression showing the variables associated with the ordinate in Figure 6 is as follows:

$$\frac{\Delta R}{f_p} = \left[(N\ B_o) \frac{32}{2} \frac{\rho}{\mu_o} K(a^2/_b2) \right] \frac{1}{f_p}$$

N	= number of turns of wire on the coil
B_o	= magnetic induction (Webers/square meter)
ρ	= resistivity of the metal under test (ohm-meters)
μ_o	= permeability of free space ($4\Pi \times 10^{-7}$– MKS units)
$K(a^2/_b2)$	= dimensionless quantity which depends on geometry through the ratio $a^2/_b2$.
ΔR	= in phase component of the detected signal, i.e. see Figure 2 (volts)
f_p	= peak frequency (Hz)

$\left[(N\ B_o) \frac{32}{\pi^2} \frac{\rho}{\mu_o} K(a^2/_b2)\right]$ - slope of the straight lines in Figure 4. (Note that there is no dependence on the sample cross section.)

With respect to the constant terms in the equation, when $a^2/_b2$ equals respectively 1, 2, 3, and 4, $K(a^2/_b2)$ is 1.248, 1.334, 1.475, and 1.607.

With respect to the coils themselves, their diameter may be from six inches to six feet. The input and sensing coils are usually arranged concentrically in spaced relation with insulation materials such as fiber glass disposed between the coils. The coils are shielded from room temperature change by insulation since variation affects output. A further compensating arrangement that has been found effective also is the use of special alloy thermal stable metals rather than copper in the conductors to reduce thermal effects. The six foot coil assembly is used in connection with security at airports in which the individual walks through the coil itself and is scanned for possession of weapons.

Throughout this description, the relation between resistivity, area, peak frequency, and resistive component divided by frequency are given as unique values at curve peaks. However, relationships to resistivity and cross-sectional area may be complex. Nevertheless, all that is needed is a repetitive signature. End effects, shadow effects, and geometric effects and magnetic effects present no problem because signatures for the same object will be exactly the same.

WHAT WE CLAIM IS:-

1. A system for identifying samples having conductive properties, comprising frequency generating means operable to provide output signals at a plurality of selected periodic driving frequencies; coil means connected to said frequency generating means and responsive to an output signal having a selected periodic driving frequency for providing a magnetic field which varies in accordance with said selected periodic driving frequency, said coil means producing an output signal having a phase and said coil means being responsive to placement of a conductive sample in said magnetic field to undergo an impedance change having a true resistive component; and means for obtaining the true resistive component of the impedance change at said selected periodic driving frequency by referencing the phase of the output signal of said coil means to within 1° of the phase of the output signal of said frequency generating means for said selected periodic driving frequency, whereby to develop signature data to identify said sample.

2. A system according to claim 1, wherein said coil means comprises an input coil connected to said frequency generating means and an output coil connected to said means for obtaining said true resistive component.

3. A system according to claim 1, wherein the coil means comprises an output coil and a balancing coil which are identical in a balanced bridge circuit.

4. A system according to claim 2 or 3, wherein said two coils are matched.

5. A system according to any one of claims 2 to 4, wherein said two coils have a rated value, there being substantially no variation in said rated value due to change in ambient temperature.

6. A system according to any one of claims 2 to 5, wherein said means for obtaining said true resistive component includes a phase sensitive detector connected to said coil means and capable of being calibrated so as to be referenced to be in phase with each said periodic signal applied to said input coil.

7. A system according to any one of claims 2 tio 6, wherein said coils comprise a primary coil and a secondary coil which have a common central axis and are in the form of hollow coils having turns spaced apart from, but adjacent to, each other.

8. A system according to any preceding claim, wherein said coil means is stable to at least one part in ten thousand.

9. A system according to any preceding claim, wherein the output signal generated by said frequency generating means has a phase with a variation of less than one-half of one degree.

10. A system according to any preceding claim further comprising dividing means for dividing said true resistive component by said selected frequency.

11. A system according to claim 10, wherein said means for obtaining said true resistive component provides, for a further sample positioned in said magnetic field of said coil means, at least one further value of said true resistive component divided by at least one frequency value, said system further comprising storage means for storing values of said true resistive component divided by a corresponding selected frequency, as provided by said dividing means, and comparison means for comparing said provided further values of said true resistive component divided by said frequency value for said second sample disposed in said magnetic field of said coil means with said stored values of each said true resistive component divided by the corresponding said selected periodic frequency.

12. A system according to claim 3, wherein said frequency generating means comprises two output leads, and wherein the coils are connected across said two output leads of said frequency generating means, two impedances are connected in series across said two output leads of said frequency generating means, one of said impedances comprising a variable impedance for balancing said coil means, and wherein said means for obtaining said true resistive component comprises a phase sensitive detector connected between a point connecting said coils and a point connecting said two impedances.

13. A system according to claim 1, wherein said frequency generating means includes output leads, said coil means including an input coil comprising a hollow coil connected across said output leads of said frequency generating means, said coil means further including a secondary coil arrangement including two matched hollow coils connected in bucking relationship and axially arranged, one with respect to the other, and adjacent to said input coil, a balancing variable resistor is connected to said secondary coil arrangement, and a phase sensitive detector is connected to a junction connecting said two matched hollow coils of said secondary coil arrangement for measuring said true resistive component.

14. A system according to any preceding claim, wherein said means for obtaining said true resistive component includes means for providing a correction for zero degree phase shift from the phase of the output signal of said frequency generating means.

15. A system according to any preceding claim, wherein said frequency generating means is operable to provide output signals having frequencies ranging from one hundred to ten thousand hertz for use in identifying metallic objects.

16. A system according to any preceding claim, wherein said frequency generating means is operable to provide output signals having frequencies ranging from one to ten megahertz.

17. A system according to any preceding claim, wherein said system further comprises a computer for comparing true resistive component values for successive frequencies with known values so as to detect identity therebetween and to issue a corresponding comparison output, said system further comprising alarm means connected to said computer and responsive to said corresponding comparison output for generating an alarm.

18. A method of identifying samples having conductive properties, comprising the steps of providing a coil system having an input coil; generating in turn a plurality of signal frequencies; applying at least one said signal frequency to said input coil of said coil system to produce a magnetic field; introducing a sample into said magnetic field of said coil system so as to cause an eddy current loss; obtaining, for said at least one signal frequency applied to said input coil and by referencing the phase of the output signal of the coil system to

within 1° of the phase of the output signal of the frequency generating means, a true resistive component of said eddy current loss so as to develop at least one true resistive component value; dividing said at least one true resistive component value by said at least one signal frequency applied to said input coil to develop at least one quotient value; and using said at least one quotient value as a function of signal frequency applied to said input coil to obtain signature data for identifying said sample.

19. A method according to claim 18, wherein said coil system comprises a balanced coil system, said method further comprising the step of balancing said coil system to provide maximum sensitivity for detection of said at least one true resistive component value caused by said eddy current loss.

20. A method according to claim 18 or 21, further comprising the steps of storing a plurality of signature data for comparison purposes, and comparing each of the signature data with the obtained signature data for the sample to identify the sample.

21. A method according to claim 18, further comprising the step of introducing a specific uniform type of metal sample of given cross-sectional area to the magnetic field of said coil system to obtain reference data values, whereby to calibrate said coil system.

22. A method of determining response characteristics for samples having conductive properties, comprising the steps of: providing a coil assembly; applying a plurality of periodic signal frequencies in turn to said coil assembly so as to provide a magnetic field for each signal frequency; introducing a plurality of the same kind of metal samples of different cross-sectional areas to said magnetic field of said coil assembly; measuring, for at least one periodic signal frequency applied to said coil assembly, the true resistive component of voltage unbalance in an output signal from the coil assembly caused by introduction of each of the metal samples; and compensating for phase-shift in the coil assembly with respect to the phase of said at least one periodic signal frequency applied to said coil assembly, whereby said true resistive component value is obtained at zero degree phase-shift, the phase of the output signal of said coil assembly being referenced to within 1° of the phase of the applied periodic signal frequency.

23. A method according to claim 22, wherein said obtained true resistive component is divided by said one periodic signal frequency applied to said coil assembly to obtain at least one corresponding quotient value and said at least one quotient value is used as a function of said at least one periodic signal frequency applied to said coil assembly to identify the sample.

24. A method according to claim 23, wherein said at least one quotient value comprises a plurality of quotient values and there is identified a peak quotient value corresponding to said frequency at which resistivity of said metal sample divided by its cross-sectional area is proportional to said true resistive component of said impedance unbalance divided by said corresponding frequency.

25. A system for identifying samples constructed and arranged to operate substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

26. A method of identifying samples substantially as hereinbefore described with reference to the accompanying drawings.

27. A method of determining response characteristics substantially as hereinbefore described with reference to the accompanying drawings.

J.A. KEMP & CO.,
Chartered Patent Agents,
14 South Square,
Gray's Inn,
London, WC1R 5EU.

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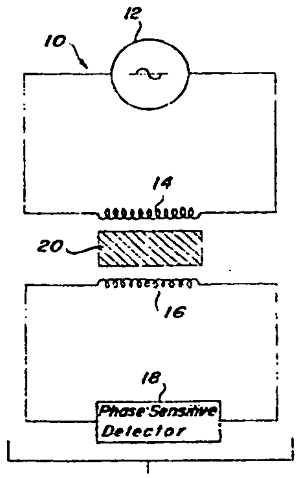


Fig.1

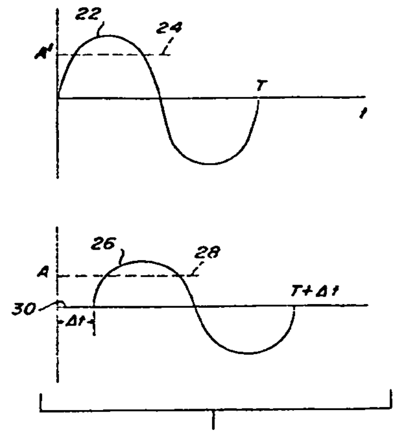


Fig.2

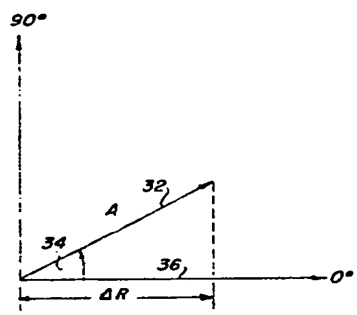


Fig.3

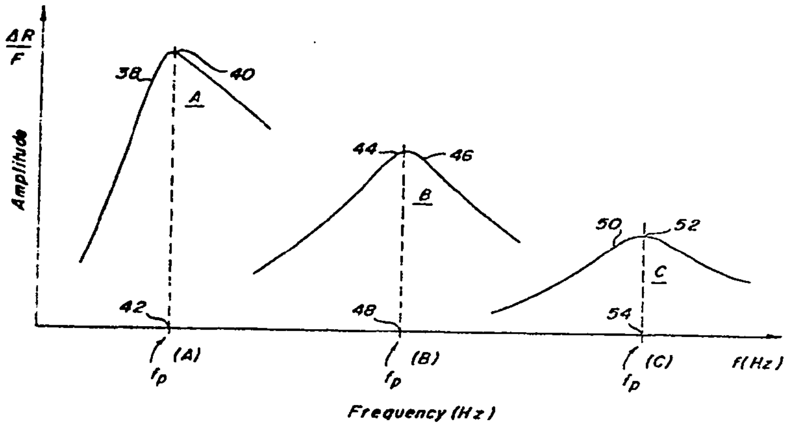

ΔR/F
Amplitude
38
40
A
44
46
B
50
52
C
42
48
54
f_p (A)
f_p (B)
f_p (C)
f(Hz)
Frequency (Hz)

Fig-4

Fig.5

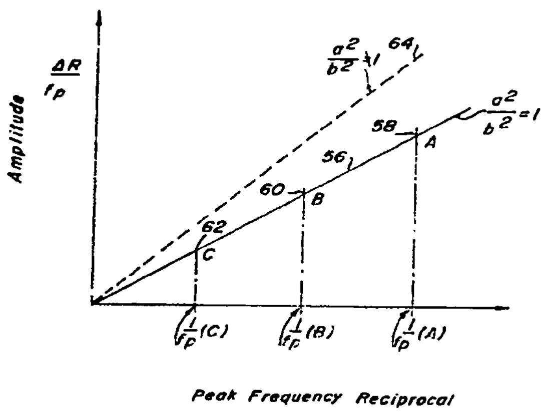

ΔR/f_p
Amplitude
$\frac{a^2}{b^2} \neq 1$
64
$\frac{a^2}{b^2} = 1$
58
A
56
60
B
62
C
$\frac{1}{f_p}$(C)
$\frac{1}{f_p}$(B)
$\frac{1}{f_p}$(A)
Peak Frequency Reciprocal

Fig. 6

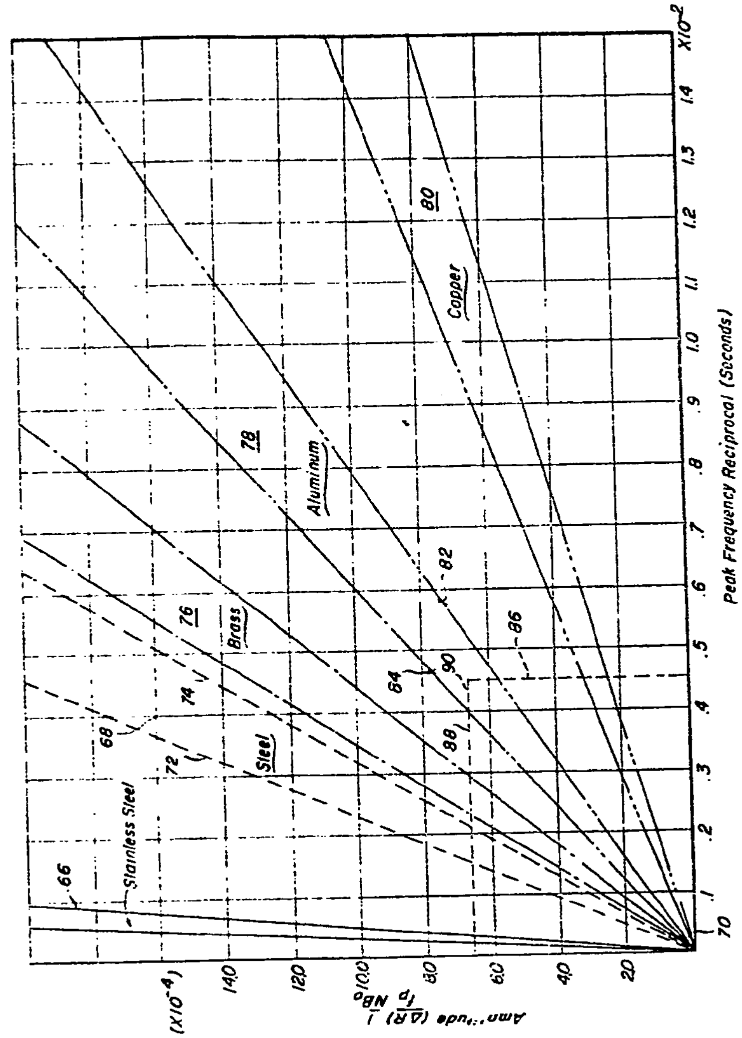

Peak Frequency Reciprocal (Seconds)
X10^-2
Amplitude (ΔR) 1/Tp NBo
(X10^-4)
Stainless Steel
Steel
Brass
Aluminum
Copper
66
68
70
72
74
76
78
80
82
86
88
90
64

Fig.7

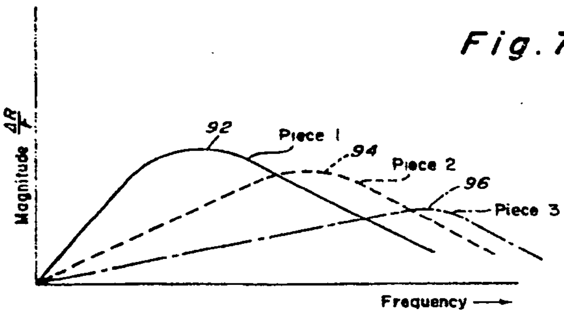

Magnitude $\frac{\Delta R}{F}$
92
Piece 1
94
Piece 2
96
Piece 3
Frequency

Fig.8

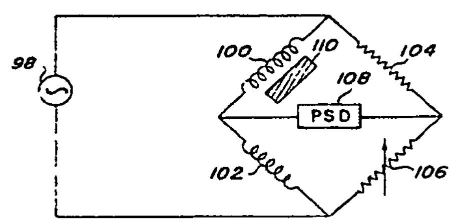

98
100
110
104
108
PSD
102
106

Fig. 9

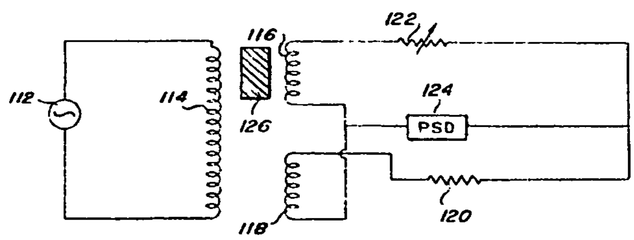
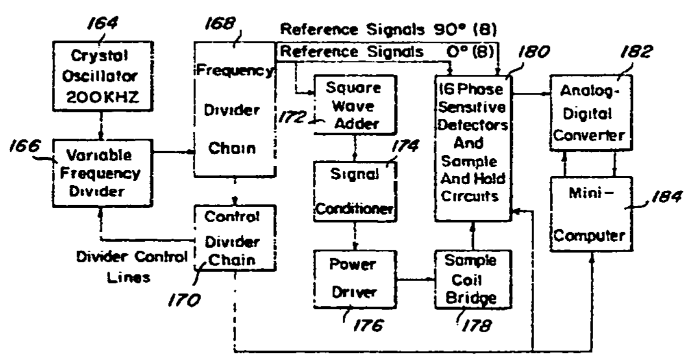

122
116
112
114
126
124
PSD
118
120

Fig. 14


164
Crystal Oscillator 200KHZ
168
Frequency Divider Chain
Reference Signals 90° (8)
Reference Signals 0° (8)
180
182
Square Wave Adder
172
16 Phase Sensitive Detectors And Sample And Hold Circuits
Analog-Digital Converter
166
Variable Frequency Divider
174
Signal Conditioner
Mini-Computer
184
Control Divider Chain
Divider Control Lines
170
Power Driver
176
Sample Coil Bridge
178

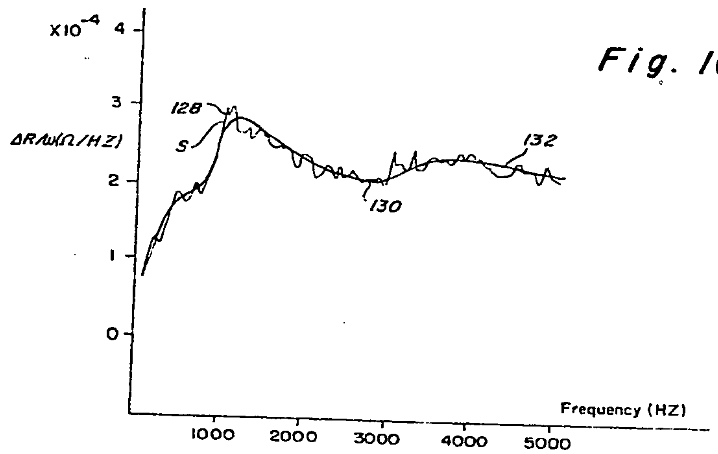

X10^-4
4
3
2
1
0
ΔR/ω(Ω/HZ)
128
S
132
130
Frequency (HZ)
1000
2000
3000
4000
5000

Fig. 10

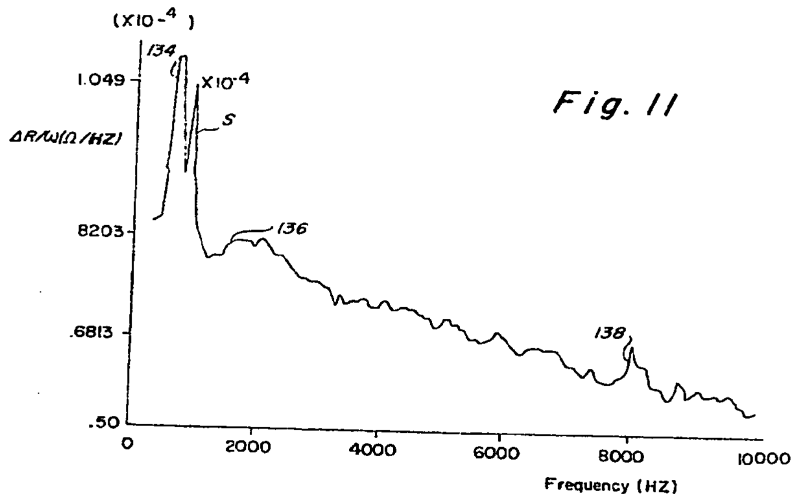

(X10^-4)
134
1.049
X10^-4
S
ΔR/ω(Ω/HZ)
8203
136
.6813
138
.50
0
2000
4000
6000
8000
10000
Frequency (HZ)

Fig. 11

Fig. 12

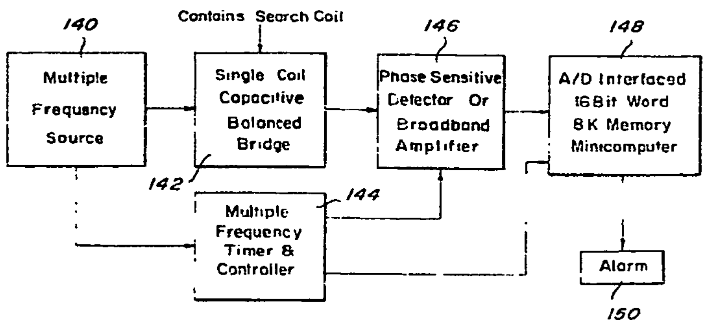
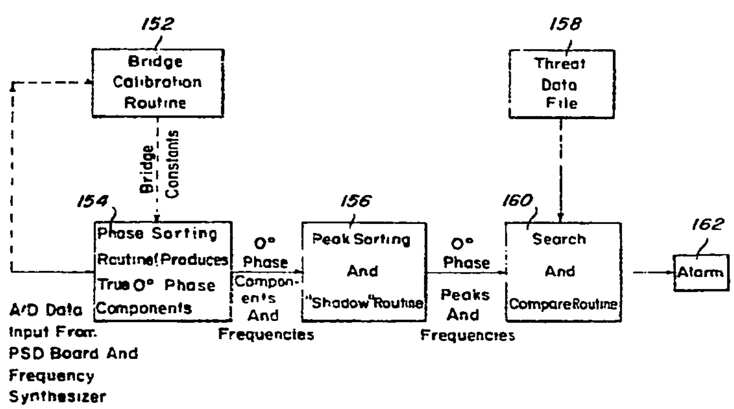

Contains Search Coil
140
Multiple Frequency Source
Single Coil Capacitive Balanced Bridge
142
146
Phase Sensitive Detector Or Broadband Amplifier
148
A/D Interfaced 16Bit Word 8K Memory Minicomputer
144
Multiple Frequency Timer & Controller
Alarm
150

Fig. 13


152
Bridge Calibration Routine
Bridge Constants
158
Threat Data File
154
Phase Sorting Routine (Produces True 0° Phase Components
A/D Data Input From PSD Board And Frequency Synthesizer
0° Phase Components And Frequencies
156
Peak Sorting And "Shadow" Routine
0° Phase Peaks And Frequencies
160
Search And Compare Routine
162
Alarm

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